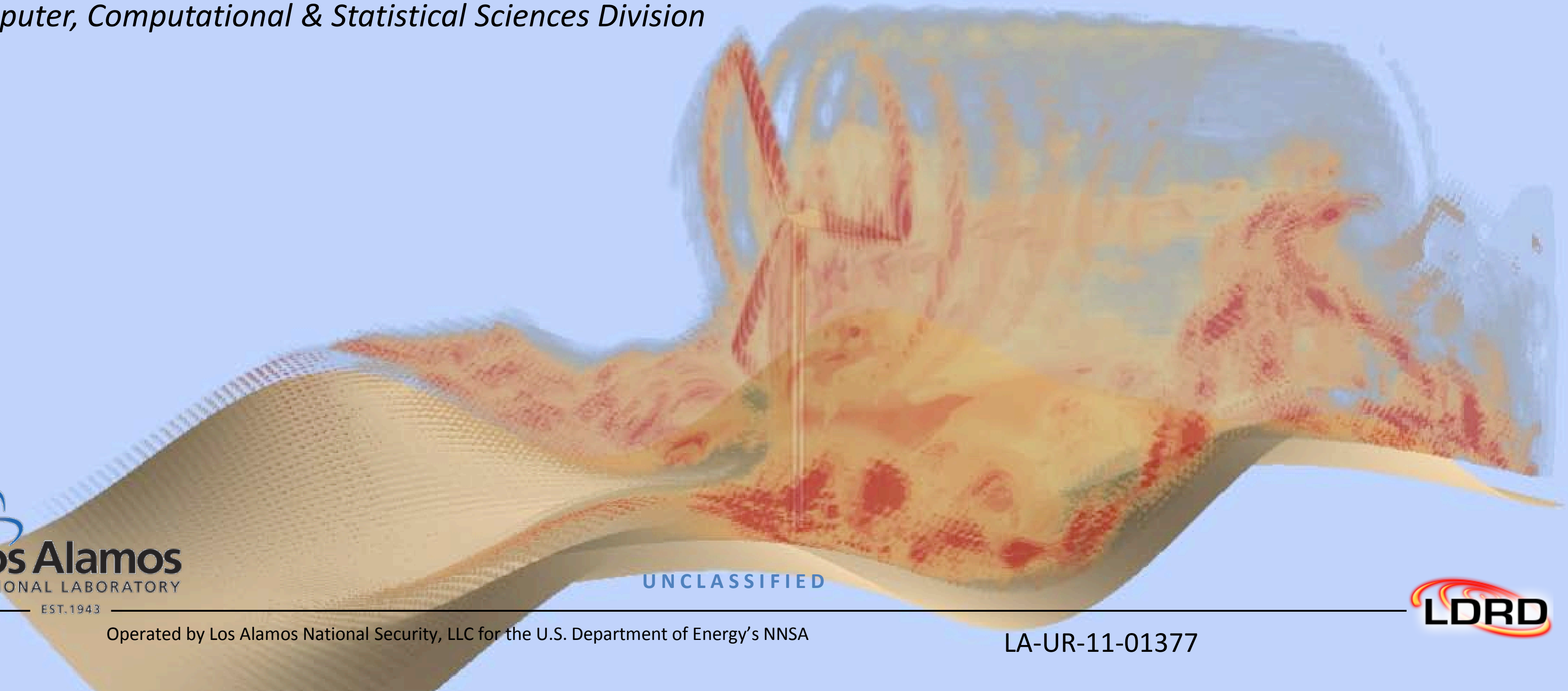
Modeling Development Activities

Adjoint Optimization
Matt Bement
X-Computational Physics Division

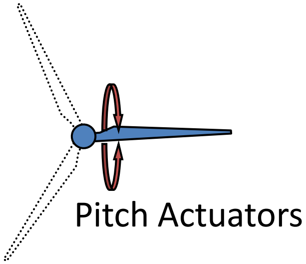
Verification and Validation with Uncertainty Quantification
Francois Hemez
X-Theoretical Design Division

Visualization and Data Interrogation
Jim Ahrens and John Patchett
Computer, Computational & Statistical Sciences Division

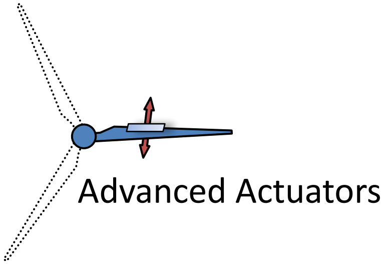


Adjoint Optimization: A Novel Approach for Exploring Active Aero Control Actuators

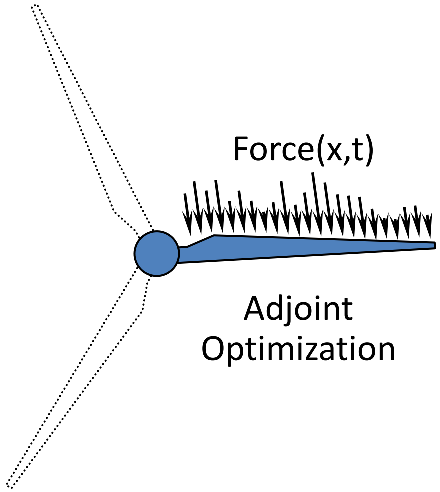
- **Today's turbines utilize blade pitch control**
  - Typically hydraulically actuated
  - Used to shed load at high wind speeds



- **Future turbines will incorporate active aero controls**
  - e.g. trailing edge flaps, microtabs, active flow control
  - Increase energy capture, minimize fatigue damage…



- **We are developing Adjoint Optimization techniques**
  - Allows gradients of a cost function to be calculated with respect to time-varying and spatially-varying forces
  - Identifies advanced actuation concepts without running a multitude of simulations or conducting expensive tests
  - Our Goal: Adjoint-based optimization employing LANL **WindBlade** code



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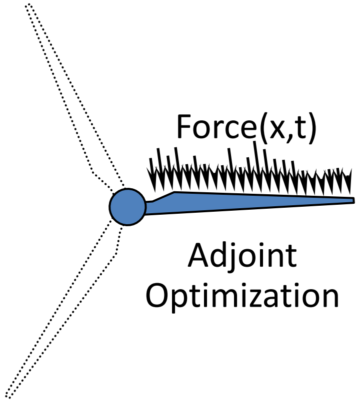
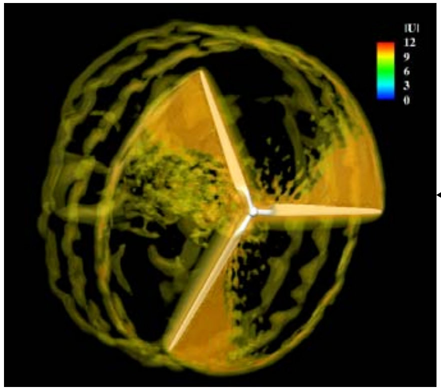
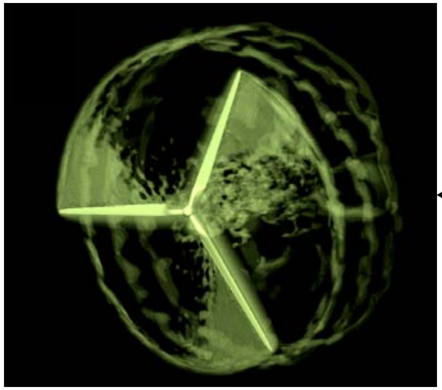
Adjoint Wind Turbine Simulation Capability

- Define a cost function "C" (e.g. power output, reaction loads)
- What should F(x,t) be to optimize C?
- Without Adjoint Method
  - Perform multiple variations of F(x,t) to optimize C
  - Not computationally tractable – includes thousands of free parameters
- With Adjoint Method
  - Use gradient-based non-linear optimization to iterate on F(x,t)
  - Two simulations per optimization case
    - one forward in time using FSI code
    - one in reverse time using adjoint version of FSI code





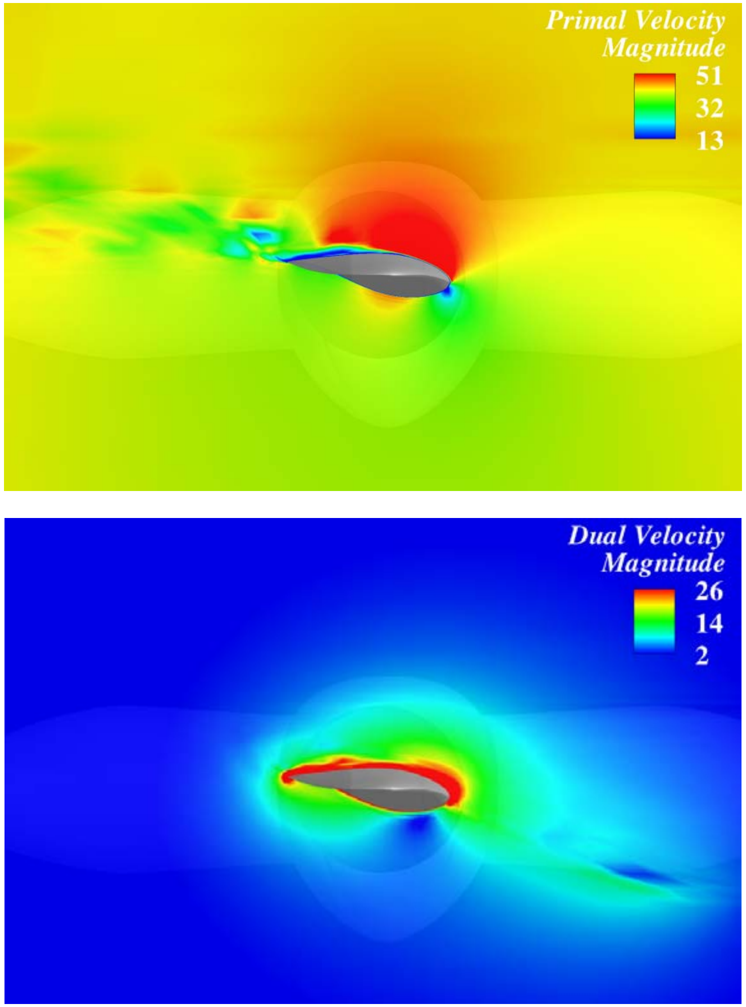
Fluid-Structure Interaction (FSI) Code



Adjoint Version of FSI Code

Current Progress

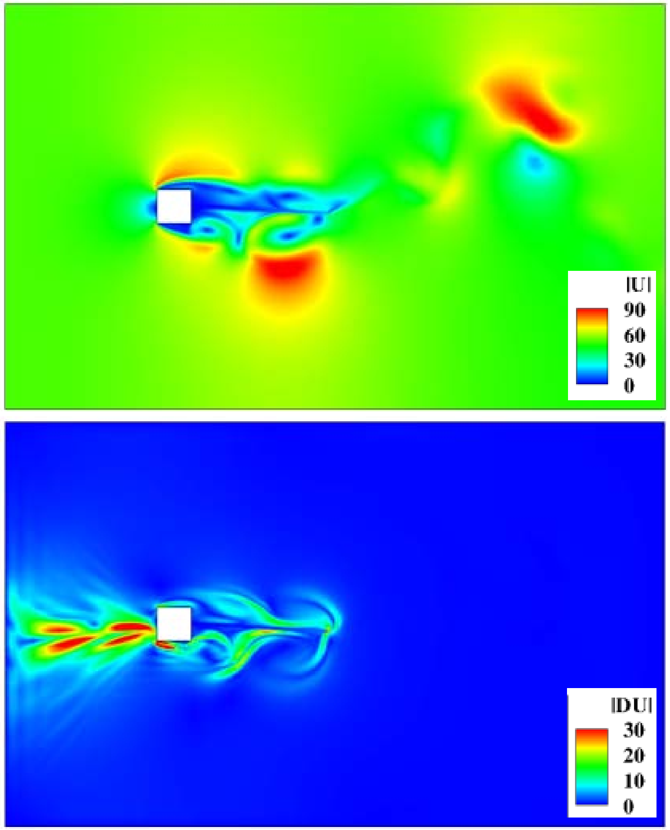
- Adjoint method formulated and implemented in fully coupled FSI code being developed under subcontract by Y. Bazilevs at UCSD
- Developed for case of incompressible Navier-Stokes equations in ALE frame, which is suitable for moving domain aerodynamics problems
- Dual formulation applied to simulation of NREL baseline 5MW wind turbine with rigid blades
- Cost function was rotor aerodynamic torque, which produced forcing for the dual problem
- Large values of dual solution obtained at suction side of blade, upstream of the blade and in trailing edge region, indicating these regions have most influence on cost function



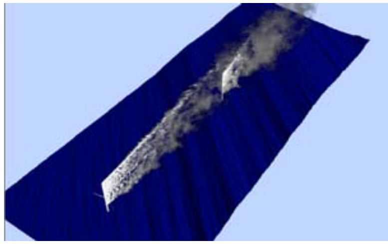
Primal (forward) and dual (adjoint) velocity for flow around a turbine blade

Current Progress/Future Plans

- Perform adjoint optimization for fully coupled FSI cases
  - Has been tested on simple 2D flexible beam
  - Will be applied to 3D simulation of turbine rotors
- Investigate adjoint formulation of WindBlade Code
  - Currently developing FSI capability for WindBlade
  - Adjoint HiGrad/FIRETEC under consideration
- Potential adjoint WindBlade capabilities
  - Controls development for turbines under realistic wind conditions
  - Damage-mitigating controls for impaired rotors
  - Expand focus from single-turbine optimization to wind plant (turbine array) optimization techniques



Adjoint for 2D, Fully Coupled FSI



Objective: Adjoint WindBlade

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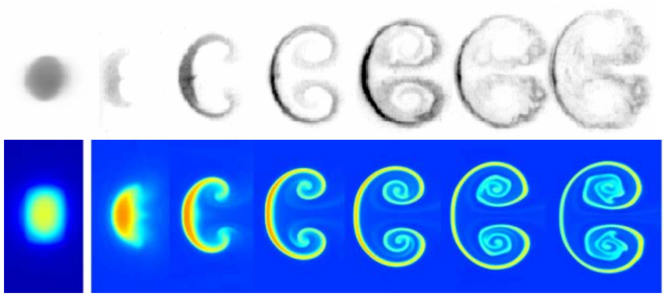
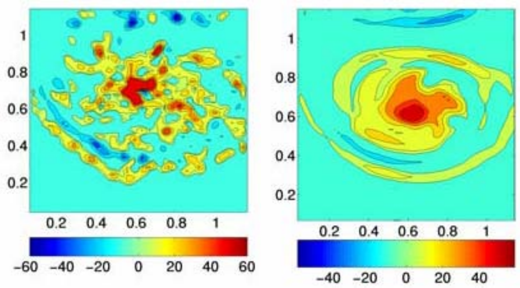
Our Modeling Efforts Benefit from LANL Weapons V&V Expertise

Verification and Validation (V&V) is a quantitative bridge between physics models, simulation, experiment

- **Verification**: Solving the equations correctly (i.e. *get the math right*)
- **Validation**: Solving the correct equations (i.e. *get the physics right*)



Gas Shock Tube Experimental Images (top)
Calculations using RAGE code (bottom)

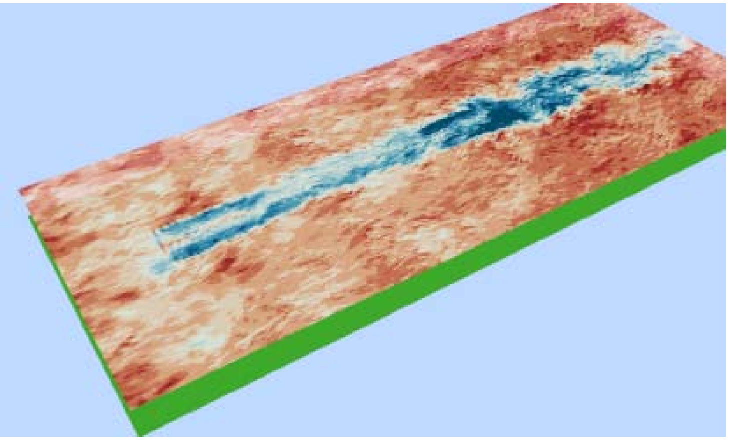


Vorticity Values for Experiment (left)
and RAGE Calculation (right)

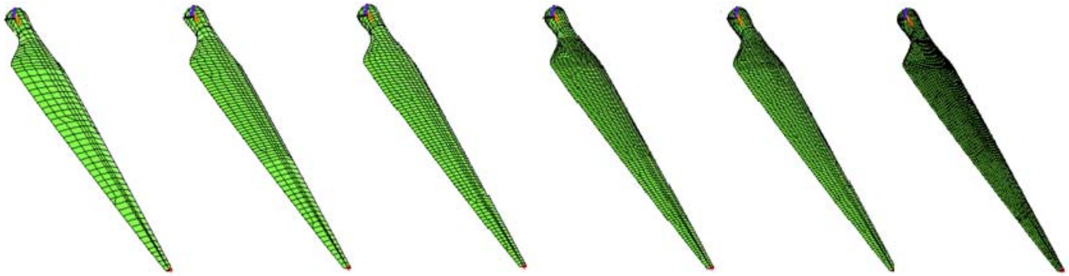
V&V Provides Confidence for Simulation Extrapolation

Code Predictions Come with Numerical Uncertainty
(just like measurements exhibit experimental variability)

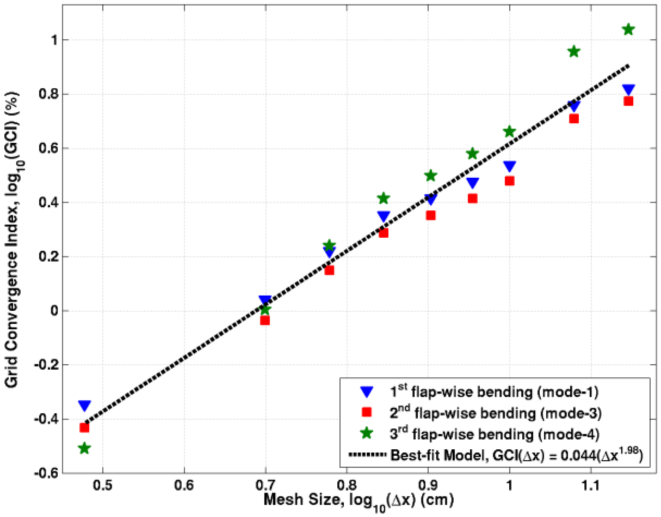
- Verification activities assess the numerical performance of algorithmic implementations
- The bounds of numerical uncertainty can be quantified for comparison with the experimental variability



V&V Give These Results Meaning



Turbine Blade Mesh Refinement Study



Asymptotic Behavior of Solution Uncertainty

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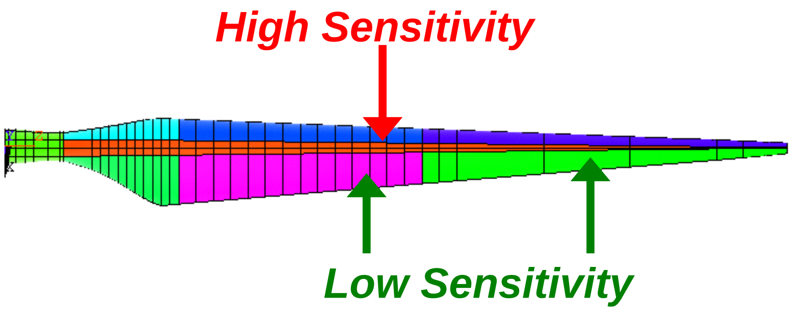
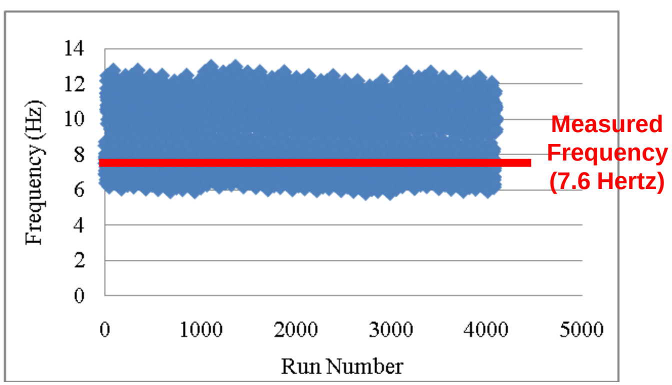
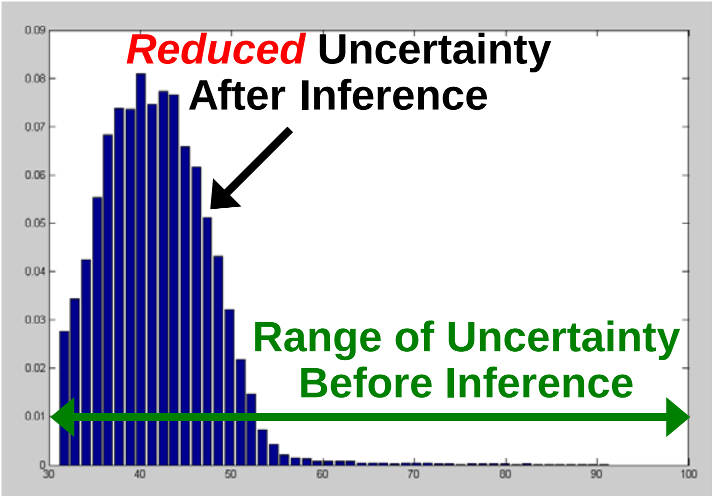
Inference Uncertainty Quantification

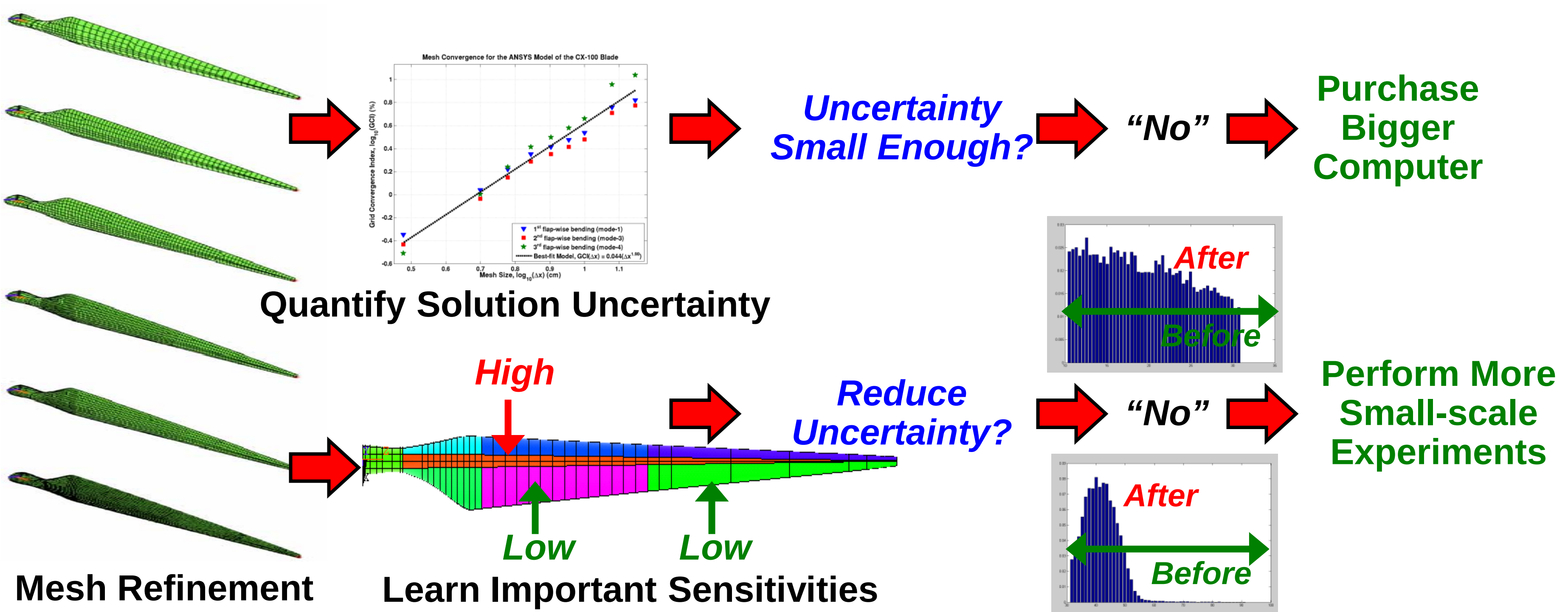
- Inference uncertainty quantification contributes to the reduction (or not!) of modeling and parametric variability
- Variance decomposition methods are used to discover the important sensitivities of our models
- Inverse methods are used to infer the modeling uncertainty that is most consistent with the experimental variability







V&V Supports Informed Resource Allocation and Decision-Making



V&V Process Developed for CX-100 Blade Model

Modal Testing Results

Statistics of Identified Frequency for Free-free Modal Testing			
Type of Mode	**Mean Value**	**Std. Dev. Value**	**Variability(1)**
First flap-wise bending	7.617 Hertz	0.004 Hertz	0.06%
Second flap-wise bending	20.167 Hertz	0.055 Hertz	0.27%
Third flap-wise bending	32.256 Hertz	0.051 Hertz	0.16%
Statistics of Identified Frequency for Fixed-free Modal Testing			
Type of Mode	**Mean Value**	**Std. Dev. Value**	**Variability(2)**
First flap-wise bending	3.221 Hertz	0.008 Hertz	0.24%
Second flap-wise bending	8.824 Hertz	0.011 Hertz	0.12%
Third flap-wise bending	19.204 Hertz	0.020 Hertz	0.11%

(1) Based on 27 replicates for the free-free tests.
(2) Based on 47 replicates for the fixed-free tests.

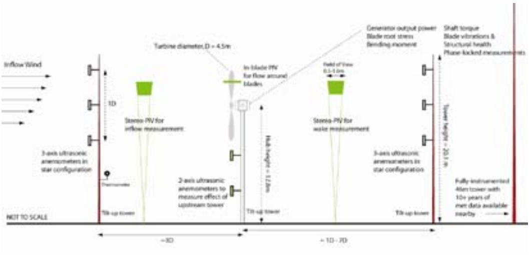
- A process was identified for complete code verification and solution verification to legitimize the model
  - Modal testing performed by LADSS students
  - Simplified blade FE model generated by IWT summer students
  - Sensitivity analysis applied to FE model varying representative properties (density and Young's modulus)
  - Gaussian process models developed to reduce the uncertainty to a probability distribution
- A rigorous application of this process will be applied to the completed, 800,000+ DOF FE blade model this year

WindBlade V&V Pedigree

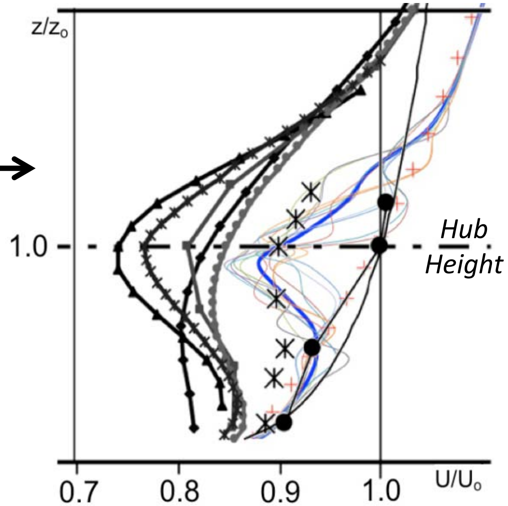
- R&D 100 winning HIGRAD/FIRETEC is compressible hyrdodynamics code underlying WindBlade
- HIGRAD/FIRETEC has been validated against several experimental datasets

HIGRAD/FIRETEC vs. the International Crown Fire Modeling Experiment (ICFME)

- WindBlade V&V Plans
  - Extension of HIGRAD/FIRETEC regression suite to WindBlade
  - Validation against available experimental datasets
  - Validation against internal experimental datasets



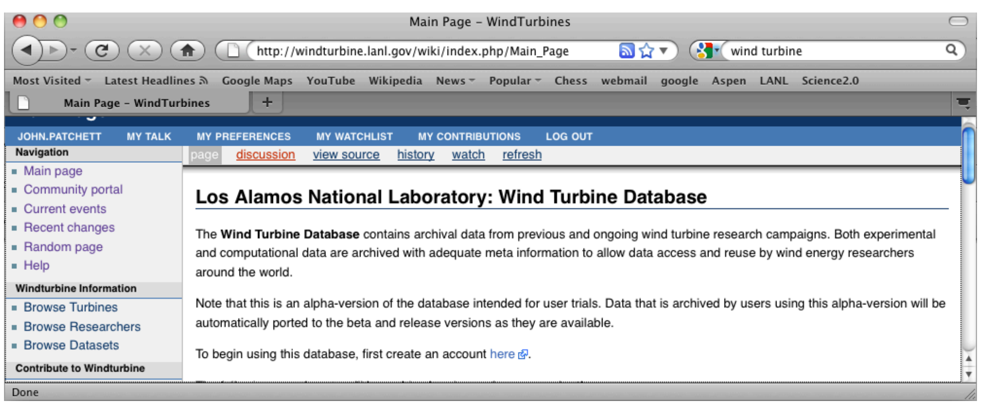
Provides Confidence in Simulations

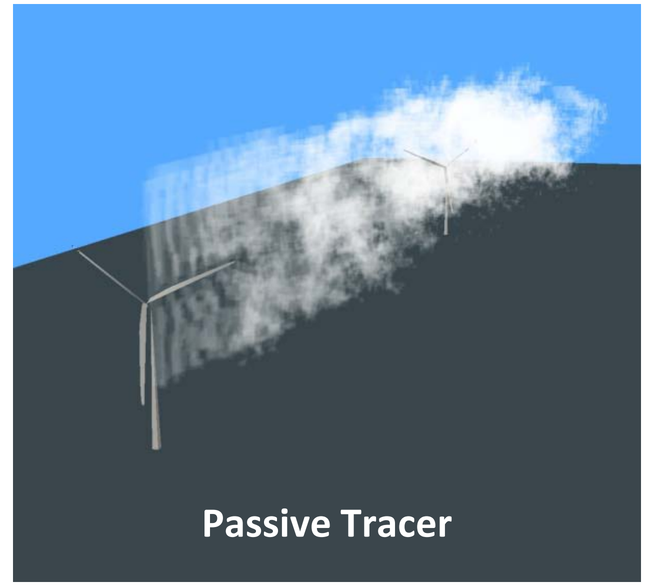


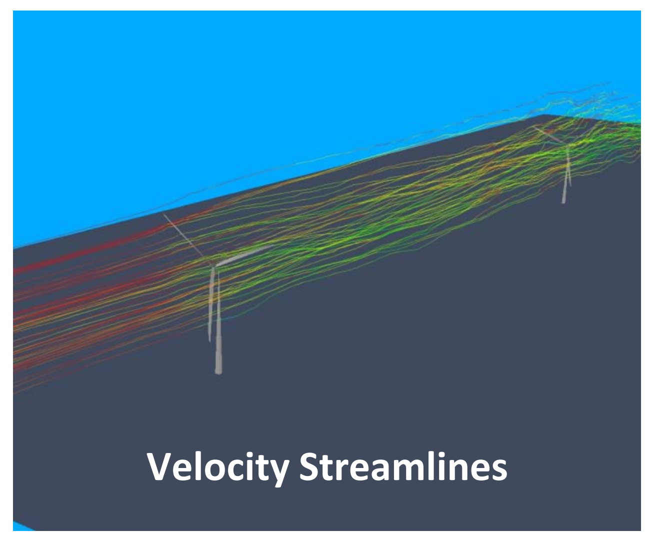
***WindBlade** turbine wake simulation (**colors**) compared with measurements (✳) and model results (**grey**/**black** curves) from Rodos et al.*

Visualization of Large WindBlade Data Sets

- Motivation
  - Allow stakeholders with differing visual analysis needs to interrogate various aspects of the datasets, gain insight, facilitate communication and decision processes, and explore "what-if" scenarios
- Production Visualization
  - ParaView allows parallel processing of each time step
  - Reader for WindBlade data in ParaView
  - Updates for reader to be included in new ParaView release
    - Multiple turbines and terrain support
  - Web delivery
  - Hardware resource support
- Data Management Support
  - Large data movement issues for visualization and analysis
  - Participation in design of a repository for experimental and numerical data (windturbine.lanl.gov)

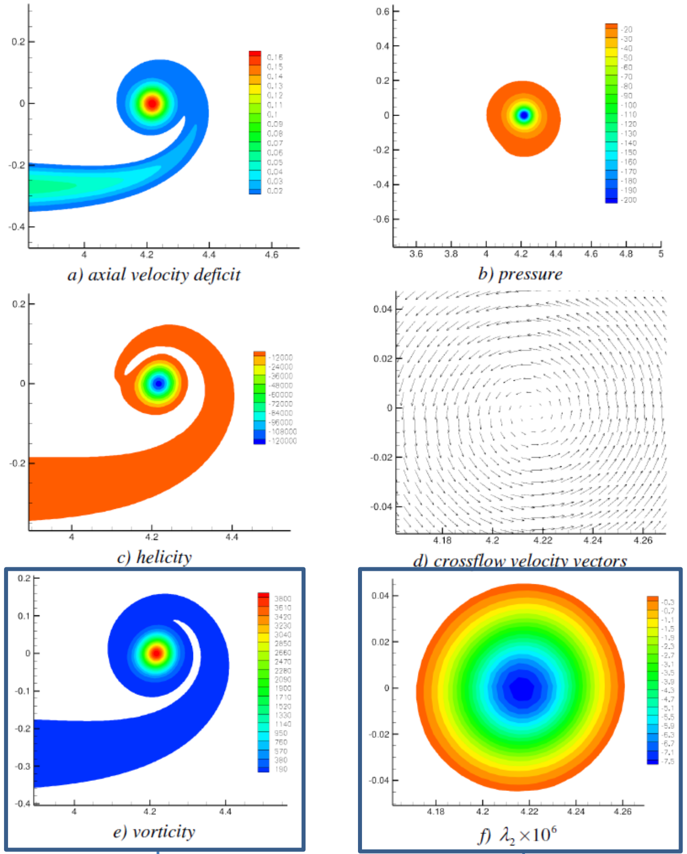



Passive Tracer


Velocity Streamlines

Extracting Meaningful Results from WindBlade

Vortex Identification Schemes

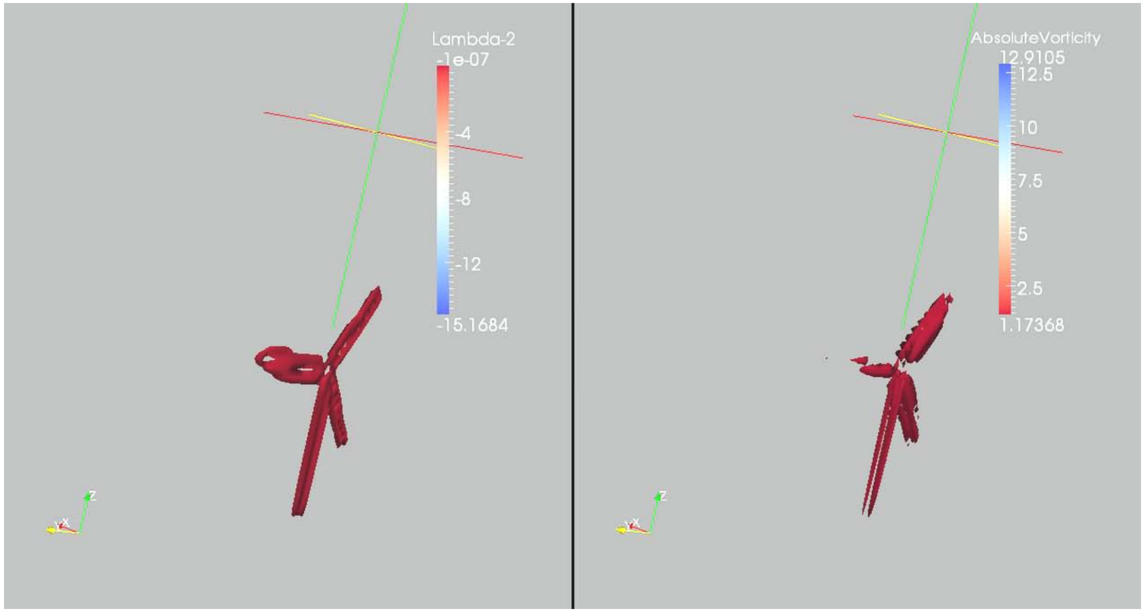


Effects of Turbulence Modeling on RANS Simulations of Tip Vortices
J. Wells, 2009

Intercomparison of Vortex Core Finding Techniques
Shafii, et.al., 2011

R&D Visualization of Coherent Structures in WT Wakes

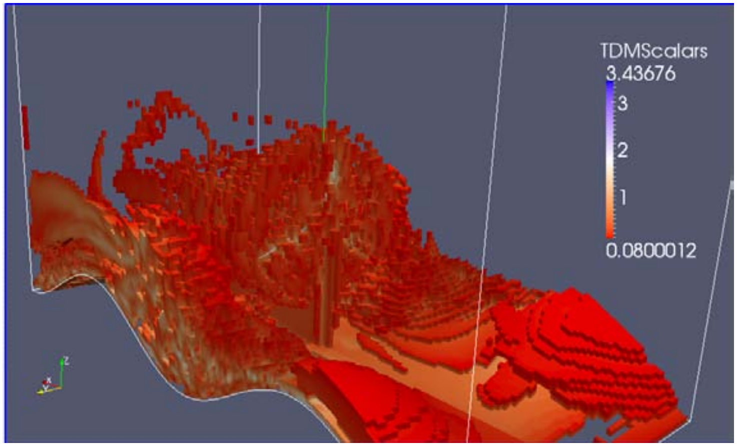
- Vortex identification and quantification
- Absolute vorticity, λ_2, simplified TDM, …
- Quantification enables better understanding and discriminating comparisons



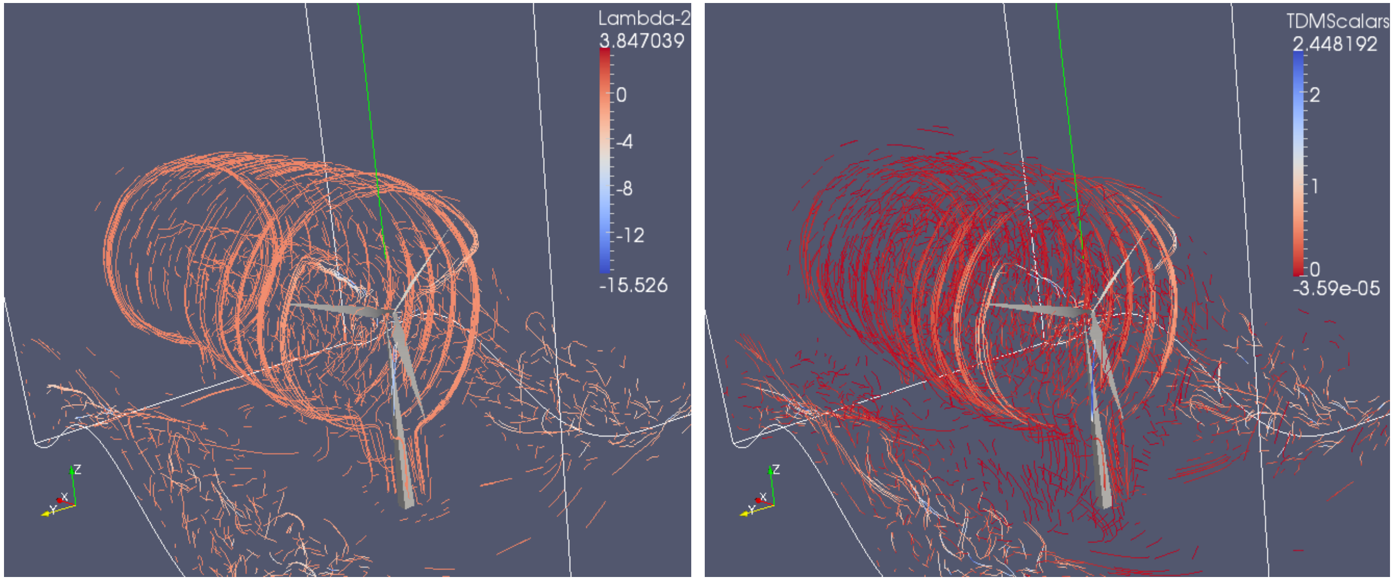
Vortex Interrogation in WindBlade
λ_2 vs. Absolute Vorticity

Future WindBlade Data Interrogation and Visualization Efforts

- Continue production visualization support
- Provide custom interfaces and web delivery of data visualization products
- Continue investigations into feature detection and quantification
- Continue UC Davis collaboration on vortex core tracing
- Support uncertainty quantification and visualization
- Add data format support for other parts of project



Simplified TDM Results Using Thresholding



λ_2 Core Lines vs. Simplified TDM Core Lines

IWT Project is On Track to Meet Proposed Deliverables

- ☑ **WindBlade turbine and plant simulation tool**
  - ☑ Multi-turbine simulations with realistic turbulence, terrain, vegetation…
  - ☑ WindBlade V&V
  - ☑ Validated CX-100 finite element model
  - ☑ Aeroelastic blades with fluid-structure interaction
  - ☑ Enhanced visualization and data interrogation interface
  - ☑ Development and implementation of adjoint optimization in reduced-scale FSI code
  - ☐ Adjoint implementation in WindBlade

- ☑ **Experimental wind turbine aerodynamics databases**
  - ☑ Large-format PIV and in-blade rotating PIV diagnostic techniques
  - ☑ Scale turbine wind tunnel campaign (aero datasets)
  - ☑ 4.5m turbine field campaign (combination aero/structural datasets)
  - ☑ 20m turbine field campaign (combination aero/structural datasets)
  - ☑ Data repository available to other researchers

- ☑ **Prototype SHM hardware and software**
  - ☑ Damage detection with active and passive sensing
  - ☐ Damage-mitigating control demonstration
  - ☑ Damage prognosis algorithm development
  - ☑ Energy harvesting to enable wireless operation
  - ☑ SHM node development on full-scale blade fatigue test
  - ☑ Field test of SHM node prototype flown on 4.5m
  - ☑ Full-scale field test of prototype SHM node, embedded in blade and flown on 20m turbine

Conclusion: ***We are Developing Wind Energy Solutions at LANL***

- We have extremely talented engineers who work well together
- We have unique expertise, resources, and ideas
- We complement the work of other labs, academia, and industry
- We are laying the foundation for a future wind program at Los Alamos